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EFFECT OF SUCROSE ON CRISPNESS OF EXPLOSION-PUFFED APPLE PIECES EXPOSED TO HIGH HUMIDITIES

SUMMARY—Explosion-puffed apple pieces, because of their hygroscopicity, rapidly lose their crispness under humid conditions. A major cause of the loss of crispness is softening of the sugars, present in the glassy or amorphous state, as moisture is adsorbed. Of these sugars, sucrose has the highest softening point. Materials higher in sucrose content can tolerate more moisture at a given temperature before they soften than materials higher in monosaccharides. The sucrose content of apple pieces is 20—30% of the total sugars. The sucrose content of pieces for puffing was increased to 80% of the total sugars by the following treatment before puffing: The pieces were first soaked in tap water 3—6 hr to reduce monosaccharide content, then soaked in 20—40% sucrose solutions several hours to increase sucrose content by osmosis and counter-diffusion of sucrose. The pieces were then partially dried, puffed and finally dried by conventional hot-air drying to 2% moisture content. Comparison of untreated and treated pieces revealed that the untreated pieces lost their crispness at 4.3% moisture and the treated pieces at 6.6%. When exposed to 75% R.H. and 72°F the untreated pieces remained crisp between 1 and 2 hr; at 75% R.H. and 90°F these pieces softened in less than 1 hr. However, the treated pieces exposed to 75% R.H. remained crisp 4—5 hr at 72°F and 2 hr at 90°F.

INTRODUCTION

EXPLOSIVE-PUFFING (Cording and Eskew, 1962) imparts a porous structure to fruits and vegetables, making them rapidly rehydratable and quick-cooking. Eisenhardt et al. (1968), in reporting the application of a new puffing gun (Heiland and Eskew, 1965) to apple pieces, pointed out that these pieces possess a desirable crispness because of their porous structure and low moisture content. As a result, great interest has been shown in using them as snacks, but their hygroscopicity seriously limits this use. Under hot, humid conditions they rapidly lose their crispness, the surface becomes sticky and they lose their acceptability as a snack. Their chances of consumer acceptance would be enhanced if the desirable properties imparted by explosive-puffing could be maintained for a reasonable period under adverse conditions.

The puffed and dried apple pieces behave like a visco-elastic polymer as they take up moisture and exhibit a wide range of textural properties. At low moistures the pieces are brittle (desirably crisp) and as they adsorb moisture they become tough and leathery, then rubbery and, finally, soft and spongy. The transition from the crisp to the leathery state occurs in the range 4—4.3% moisture, the pieces pass through this moisture range after 30—40-min exposures to atmospheres of 75% R.H. and 90°F. An investigation was undertaken to develop apple snacks able to withstand hot humid conditions for a longer time before losing their crispness, and to keep the highly desirable porous structure imparted by explosive-puffing.

As suggested by White and Cakebread (1966) the loss of crispness is caused by the breakdown of the glassy or amorphous sugars in the apple slices. Glucose, fructose and sucrose, the 3 major constituents, are in the amorphous state. Hence, either high temperature or high humidity or both break down these polymers into sugar solutions.

Amorphous sugars are more hygroscopic than their corresponding crystalline forms. Crystalline sucrose and dextrose are practically anhydrous below 80% R.H. (Shotton and Harb, 1965),

Table 1—Physical properties of sugars present in apples (York Imperial variety).

Sugar	Mol wt	Crystalline form		Amorphous form	
		Critical R.H.	M.P. °C	Tg °C	AMT[1]
Glucose	180	80	146	20–35	1.5
Fructose	180	55	102–104	–	6.0
Sucrose	342	80	188	67	3.0

[1] Amount expressed as g per 100 ml juice. This is a typical example.

Table 2—Leaching sugars out of half apple segments (York Imperial) at 80°F.

	After 1st leach	After 2nd leach
% Total sugars leached	56.0	79.7
% Total solids leached	13.0	16.5
% Nonsugar solids leached	40.9	50.4
Water uptake (% total water)	6	0
Duration (hr)	4	2½

whereas crystalline fructose begins to adsorb moisture significantly only above 50% R.H. (Dittmar, 1935). On the other hand, Figure 1 shows the greater hygroscopicity of the corresponding amorphous forms of these sugars. Fructose and sucrose begin to adsorb moisture above 15% R.H. while glucose begins to adsorb moisture significantly above 60% R.H. From this it appears that glucose would offer the best protection since it is the least hygroscopic of the three. However, this is not so, because of the low temperature of amorphous glucose and the even lower softening points of supercooled glucose solutions.

Of these 3 sugars, sucrose has the highest softening temperature, 65°C (White and Cakebread, 1966). Using the terminology of polymer science, the softening temperature is sometimes called the glass transformation temperature (White and Cakebread, 1966) or the apparent second-order transition (Duck and Cross, 1957). For glucose White and Cakebread (1966) reported it to be at 20–35°C and while there is no value reported in the literature for fructose, it can be inferred from basic principles that it would be equal to or even less than that of glucose. Fructose has the same molecular weight and its crystalline melting point has been reported to be less than that of glucose (Bates and Associates, 1942).

In addition, the effect of moisture on the softening point is of importance. Duck et al. (1957) state that for each additional 1% of water, the glass transformation temperature of amorphous glucose is lowered 8°C (14°F). Also, Dittmar (1935) reported that amorphous fructose containing 1% moisture remained plastic at 25°C. In Table 1, the critical relative humidities, softening points, crystalline melting points and molecular weights have been summarized for the glucose, fructose and sucrose.

York Imperial apples were used by Eisenhardt et al. (1968) in their studies and in this work. The sugars in these apples consist of around 70–80% monosaccharides (glucose and fructose) and 20–30% sucrose. A typical analysis is included in Table 1. Based on the foregoing ideas and the large relative amounts of glucose and fructose, these 2 sugars can be implicated as being chiefly responsible for the rapid loss in texture of untreated pieces.

If these monosaccharides could be replaced with sucrose, a sugar having a higher glass transformation temperature, resistance to loss of crispness would be increased. This was successfully done in 2 steps: First, the monosaccharides were leached out and secondly, sucrose was added to pieces by soaking them in 20–40% sucrose solutions. As a result, apple snacks which normally lost their crispness in 40 min now retained their crispness for 2 hr at 75% R.H. and 90°F.

MATERIALS & METHODS

Analysis of sugars

Fresh apples (peeled, cored and sliced) were finely chopped in a Waring Blendor. Partially dried apple slices were cut into small pieces, while completely dried apple slices were ground to a coarse powder. A weighed portion of the latter 2 samples was reconstituted to a fresh apple moisture level (85% H_2O) in a Waring Blendor.

Juice from the chopped apple mash was squeezed through cheese cloth. The recovered juice was clarified with neutral lead acetate before analysis for glucose, fructose and sucrose.

Glucose and fructose were determined by the colorimetric method of Ting (1956). Furuholmen et al. (1964) recommended that absorbance of the ferrocyanide-argenomolybdate complex be measured in the 740–750 μ region. We found the wave length maximum to be at 720 μ using a Hitachi-Perkin-Elmer Spectrophotometer Model 139. The glucose and fructose content was expressed as g per 100 ml original juice. The sucrose in the sample was determined after inversion with HCl. 2 ml of concentrated HCl was added to an aliquot of the lead-free filtrate and heated at 70°C for 10 min (first 3 min the sample was agitated). After hydrolysis the sample was cooled, neutralized and analyzed as described by Ting. Results are reported as g per 100 ml original apple juice.

Moisture

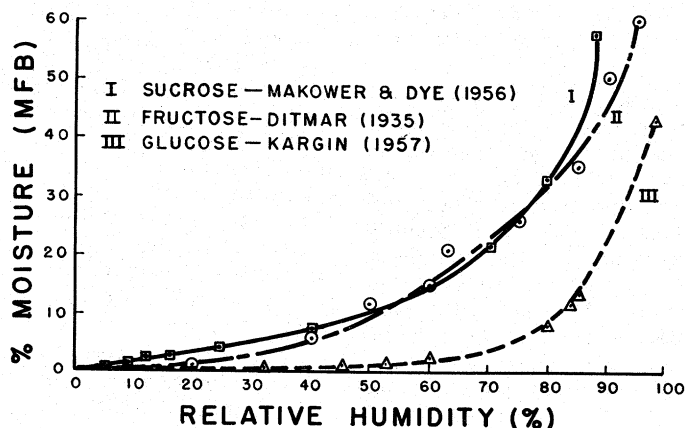Moisture content was determined by the standard vacuum oven method. Samples con-

Fig. 1—Moisture sorption isotherms for amorphous sugars 25°C.

I   SUCROSE—MAKOWER & DYE (1956)
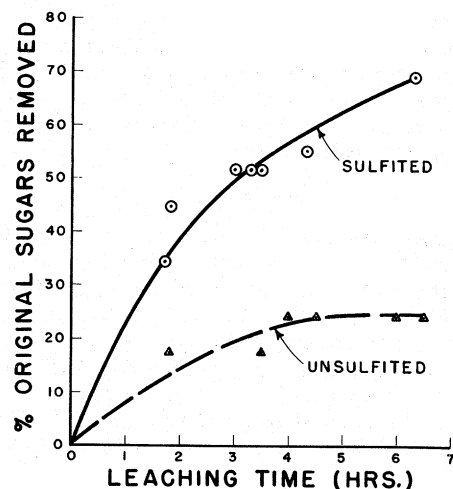II FRUCTOSE—DITMAR (1935)
III GLUCOSE—KARGIN (1957)

Fig. 2—Leaching of sulfited and unsulfited apple pieces (Golden Delicious).

Table 3—Composition of half apple segments (York Imperial) before and after leaching.

Constituent	Before leach	After 1st leach	After 2nd leach
Moisture (%)[1]	84.6	92.2	95.0
Total sugars (%)[2]	12.32	5.13	2.43
Monosaccharides (%)[2]	10.05	4.36	2.20
Sucrose (%)[2]	2.27	0.77	0.23
Acid (%)[2]	0.452	0.180	0.05
Ash (%)[2] (minerals)	0.057	---	0.025

[1] As-is basis.
[2] Grams per 100 ml juice.

Table 4—Soaking leached[1] apple pieces in 20 and 40% sucrose solutions.

Constituent	20% sucrose solution		40% sucrose solution	
	Before	After	Before	After
Moisture (%)	95.0	84.7	94.0	75.1
Monosaccharides (%)[2]	2.20	1.48	1.82	1.12
Sucrose (%)[2]	0.23	12.4	0.62	23.4
% Gain or loss of solids[3]	−16%	−18.3%	20%	+13.0%
Duration	(5 hr)		(5 hr)	
Temperature	80°F		80°F	

[1] 2 leachings.
[2] Grams per 100 ml juice.
[3] Based on original solids.

taining more than 10% moisture were dried at 70°C under vacuum for 16 hr. Samples containing less than 10% moisture were dried at 84°C under vacuum for 16 hr. Results are expressed on an as-is basis.

Acid

Titratable acidity was determined by the Glass Electrode method as described in AOAC (1965). The titratable acid was calculated as grams of malic acid per 100 ml juice.

Preparation and puffing of apples

Except for the leaching, soaking and acid addition the process employed to prepare the pieces and to puff them is essentially the same as that described by Eisenhardt et al. (1968). Mature, sound York Imperial apples were used in all runs except for the experiment showing the effect of sulfiting on the leaching rate; in this experiment Golden Delicious apples were used.

Leaching was done in tap-water (70–80°F); 80–120 lb of slices were used and the leachings lasted 4–6.5 hr. After leaching the pieces were soaked in 20–40% sugar solutions for 4–6.5 hr. All the leachings and the soakings in sucrose solutions used the same ratio of apple pieces to liquid: 1 part by weight of slices to 2 parts by weight of liquid. The slices were weighed before and after each step after being allowed to drain for 15–20 min. Samples were taken for analysis before and after each step; the liquid bath was checked periodically with a refractometer.

The dry acid was applied to the pieces before puffing by tumbling the partially dried pieces with powdered furmaric acid. Sodium silico aluminate to prevent sticking or agglomeration, as described by Eisenhardt et al. (1968), was not required.

Testing the dried puffed apple pieces

Atmospheres of about 75% R.H. were provided by desiccators containing saturated NaCl solution (Wexler and Hasegawa, 1954). These were kept at constant temperatures of 72 and 90°F. Pieces of known moisture content were placed in small aluminum weighing dishes and weighed to the nearest 0.1 mg. Duplicate samples were then placed in the desiccator and after a definite period of time were rapidly withdrawn. 1 sample was weighed to determine the moisture pickup while the other was tasted immediately. In this way the textural characteristics of the apple pieces were correlated with moisture content.

RESULTS & DISCUSSION

Interchange of sugars

Soaking the apple segments in tap-water for 4–6.5 hr removed as much as 80% of the sugars originally present. However, to effectively leach out this amount the pieces must be soft and 2 leachings are required. Sulfiting the pieces softens them sufficiently to increase the leaching rate. Figure 2 illustrates this. For about the same period of time leaching in tap-water removes 69% of the sugars from the sulfited apple pieces and only 24% from the unsulfited apple pieces. No other methods of softening were studied since the sulfiting step is an integral part of the processing that apples undergo before explosive puffing.

The data showing the effect of sulfiting on the leaching rate were obtained from a single 6.5-hr leaching. Table 2 shows the effect of 2 leachings. Using the same total time the first leaching lasted 4 hr while the second lasted 2½ hr. The data presented are typical of many runs

carried out using York Imperial apples at the same leaching conditions; they reveal that solids other than sugars were lost and that the apple pieces picked up water during the first leach but none during the second. The amount of water picked in the run was 6% over that originally present. Sugar continued to diffuse out during the second leach and by using 2 leaches 80% of the sugars were removed. These data were obtained from an over-all material balance using weights taken before and after each step plus the analytical data presented in Table 3. It shows the changes in the relative amounts of the sugars, acid, minerals (ash) and moisture before and after each leach. The relative amounts of the sugars decreased while the moisture content increased after each leach although, in the second leach, this probably reflects loss of solids rather than moisture absorption.

Sucrose was added to the pieces by soaking them in sucrose solutions containing 20–40% sucrose. Table 4 shows the effect of sucrose concentrations; as with the leaching experiments these data are typical. As expected, water flowed out of the pieces because of the difference in osmotic pressure and sucrose diffused into the pieces because of the difference in sucrose concentration. The magnitude of each change was proportional to the sucrose concentration. Another important fact revealed by the data is in the gain or loss in solids. The 40% solution added enough sucrose to overcome the amount of nonsugar solids lost during 2 leaches; this is shown under the column headed "before." Enough sugar was added by the 40% solution to cause a 13% increase in weight (based on the original total solids) while the 20% sucrose solution did not add enough sucrose to make up for the weight lost.

Adding back acid

During leaching, acid diffuses out and as a result the pieces when puffed and dried were too bland. The acid content of apples is primarily malic and this was replaced by adding either malic or fumaric acid to the sucrose solutions. Volatile flavor constituents were also added by adding apple essence to the sucrose solutions. However, when acid was added back in this manner, inversion of sucrose took place during the predrying and puffing steps and in the dry product during storage. As a result, the pieces showed no improvement in retaining crispness under hot humid conditions.

Since the pieces without acid were too bland even with flavor added, some method of adding acid without inverting the sucrose had to be found. Eisenhardt et al. (1968) pointed out that before apple pieces are explosion-puffed they should be coated with sodium silico aluminate to prevent sticking. However, after the pieces are modified, the treatment to

Table 5—Acid addition by tumbling.

Acid used (% dry wt)[1]	Acid in dried puffed product[2]
1.2	0.17
1.8	0.22
2.4	0.23

[1] Dry weight of apple pieces prior to puffing.

[2] Expressed as g malic acid per 100 ml juice.

Table 6—Relative amounts of sugars in explosion-puffed apple snacks made from York Imperial apples.

	No treatment	Treated[4] (no acid)	Treated[4] (acid)[5]	Treated[4] (acid)[3]
Sugar[1]				
glucose	2.30	1.05	3.42	1.66
fructose	6.77	1.77	3.77	2.19
sucrose	3.64	10.73	5.25	10.91
Acid[1]	0.314	0.05	0.25	0.23
Moisture[2]	2.3	1.41	1.63	1.88

[1] Grams per 100 ml juice.

[2] As-is basis.

[3] Tumbled with 2.4% fumaric acid by weight.

[4] Puffing with leaching and soaking in 40% sucrose.

[5] Acid added to sucrose solution.

prevent sticking is unnecessary and fumaric acid was substituted for the aluminate. Tumbling the pieces 20 min with 1.8–2.4% fumaric (based on the dry weight) gave the maximum amount of acid that the pieces were capable of picking up. Table 5 shows the amounts of acid picked up by the pieces dusted with fumaric acid. Fumaric acid was used rather than malic acid because of its extremely low hygroscopicity and stronger acidity; less fumaric acid than malic is required to overcome blandness (Gardner, 1966).

Table 6 shows the relative amounts of sugars and acid in explosion-puffed apple snacks made under 4 different conditions. These processing conditions were: (1) puffing without leaching and soaking in sucrose solutions, (2) puffing with leaching and soaking in 40% sucrose solution (no acid added), (3) the same as (2) but acid was added to the sucrose solution, and (4) puffing with leaching, soaking and acid added by tumbling with fumaric acid.

The data reveal that pieces puffed from York Imperials without the leaching and soaking steps contained relatively large amounts of monosaccharides. They further show that leaching followed by soaking reversed the relative amounts of sucrose and monosaccharides and removed most of the acid. Adding acid in the soaking step raised the acid level; but the data show that the acid caused inversion of the sucrose reversing the relative amounts of monosaccharides and sucrose. This was reflected in the poor resistance of these particular pieces when exposed to 75% R.H. and 90°F. However, tumbling with fumaric acid prior to puffing raised the acid content almost to its original amount. This amount was sufficient to overcome the blandness of the pieces with no acid added during the soaking step and at the same time inversion of the sucrose was avoided.

Resistance to hot humid conditions

Crispness was determined by an expert panel of 3 tasters. Snapping the pieces between the fingers does not give a true indication of the crispness; the pieces must be chewed to accurately evaluate their crispness. Hence, it was impossible to set up an objective measuring test and

Table 7—Organoleptic comparison of treated and untreated apple snacks exposed to 75% RH at 72 and 90°F.

Temp (°F)	Exposure time (hr)	Untreated snacks % Moisture[1]	Untreated snacks Texture	Treated snacks % Moisture	Treated snacks Texture
72	0	2.3	Crisp	1.4	Crisp
72	1	3.9	Crisp	2.6	Crisp
72	1–¼	4.3	Tough and chewy	2.7	Crisp
72	2–¾	6.2	Tough and chewy	4.3	Crisp
72	5	8.1	Rubbery	6.1	Crisp
90	0	2.3	Crisp	1.4	Crisp
90	½	4.0	Crisp	3.3	Crisp
90	¾	5.0	Tough and chewy	4.3	Crisp
90	1	5.9	Tough and chewy	4.5	Crisp
90	2	9.1	Tough and chewy	6.6	Crisp
90	2–¼	—	—	6.8	Tough and chewy
90	2–½	9.6	Rubbery	7.4	Tough and chewy

[1] As-is basis.

Table 8—Resistance of snack items exposed to 75% R.H. and 90°F.

Snack item	1 hr	2 hr	3 hr	4 hr	4.5 hr
Apple snacks (untreated)	Tough & chewy	—	—	—	—
Apple snacks (treated)	Crisp	Crisp	Tough & chewy	—	—
Potato chips	Crisp	Crisp (oily)	Crisp (oily)	Tough & chewy	—
Corn chips	Crisp	Marginal	—	—	—
Pretzel sticks	Crisp	Crisp	Crisp	Marginal	Tough & chewy

to correlate resistance of texture loss with the relative amounts of sucrose and monosaccharides, except on a gross scale.

Puffed apple pieces made from York Imperial apples lose their crispness when they reach a moisture content of 4.3%. The sugars consist of 20–30% sucrose and 70–80% monosaccharides. When the monosaccharides are replaced with sucrose so that the sugars consist of 70–80% sucrose and 20–30% monosaccharides this initial value is around 6.8%. Table 7 shows how the relative amounts

of these sugars affect the resistance to hot humid conditions.

Treated and untreated snacks were simultaneously exposed to 75% R.H. at 72 and 90°F and their texture evaluated organoleptically at various exposure times. Several aluminum dishes containing treated snacks and several containing untreated snacks were placed in 2 desiccators (atmosphere 75% R.H.) kept at 72 and 90°F, respectively. In every test there were 2 dishes each of known tare and each containing a known weight of treat-

ed and untreated snacks, respectively; the other dishes and their contents were not weighed. When a desiccator was opened, the 2 dishes of known weight were quickly wrapped in aluminum foil for subsequent weighing; the other dishes were taken out and immediately tested organoleptically by the 3 expert tasters, who noted their texture. After the other dishes were weighed, from the known original moisture content and the weight increase, the moisture content for the corresponding exposure time was calculated. The treated and untreated snacks tested came from a large batch of each, which were kept in polyethylene bags. These batches had been allowed to equilibrate for several days at 72°F and at the start of the test a sample was taken for moisture analysis. This value was used to calculate the new moisture content after a given exposure.

The calculated moisture contents corresponding to each exposure time are shown in Table 7 for untreated and treated snacks; also included are the descriptions of the texture corresponding to these exposure times. The terms used in this table are to be construed in their popular meanings. When a piece is no longer crisp it is no longer acceptable, but the terminology used serves to indicate a qualitative change in texture from crisp to rubbery as moisture is absorbed.

The data reveal that at 72°F the untreated pieces after 1.25 hr were no longer crisp, having now reached a moisture content of 4.3%. The treated pieces after the same exposure were still crisp and, in fact, after 2.75 hr when they reached the same moisture content of 4.3% they were still crisp. Even after 5 hr of exposure, having reached a moisture content of 6.1%, they were still accept-

ably crisp while the untreated pieces after 5 hr of exposure had become rubbery.

Higher temperatures shorten the resistance time as the data for the 90°F exposures reveal. At 90°F the untreated pieces passed their critical moisture content between 30 and 45 min of exposure, whereas the treated pieces were still crisp after this exposure. The treated pieces maintained their crispness for 2 hr, after which they reached a moisture content of 6.6%; 15 min later, having reached a moisture content of 6.8%, the pieces lost their crispness. Thus, these data revealed that by reversing the relative amounts of sucrose and monosaccharides the resistance to loss of crispness under adverse conditions can be significantly improved.

Finally, a comparison was made with some snack items currently available on the market. Table 8 shows how potato chips, corn chips and pretzel sticks compared with explosion-puffed apple snacks when exposed to 75% R.H. and 90°F. The treated apple snacks lasted longer than the corn chips but not as long as the pretzel sticks and the potato chips. However, potato chips become oily within 2 hr. It can be concluded that reversing the relative amounts of monosaccharides and sucrose improves the resistance of apple snacks to hot humid conditions to the point where they compare favorably with other snack items.

Whether these modified explosion-puffed apple snacks will find a place on the consumer's snack list is beyond the scope of this paper. Nevertheless, this work leads to 2 conclusions: (1) The relative amounts of sucrose and monosaccharides affect the textural properties of dried apple snacks, and (2) diffusion may be used to interchange constituents of food items.

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